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Quantum Simulations of Condensed Matter Systems Using Ultra-Cold Atomic Gases

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14. ABSTRACT

The theory tasks in this proposal were focused on guiding experiments and on developing better theoretical understanding of models and systems relevant for ultracold atom quantum simulation. Furthermore theory provided quantitative calculations to which quantum simulations could be compared to, and studied topics motivated by the program but of more general importance. Those tasks included the investigation of the following: Bosonic Quantum Gases in Optical Lattices; Strongly Interacting Fermionic Gases; Quantum Magnetism; Molecular Gases

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(MURI FY07) QUANTUM SIMULATIONS OF CONDENSED MATTER SYSTEMS USING ULTRA-COLD ATOMIC GASES

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The MURI program "Quantum simulations of condensed matter systems using ultra-cold atomic gases" has had tremendous impact on the field of quantum simulations. It has lead to a number of major experimental and theoretical breakthroughs in many research groups. Highlights include the pioneering of quantum gas microscopy, the realization of polaronic Fermi gases, quantitative quantum simulations of strongly interacting Fermi gases, single site study of the superfluid-Mott transition, study of the Stoner instability and the first demonstration of quantum magnetism in optical lattices. This MURI program lead to 229 publications in refereed journals, including 13 papers published in "*Nature*", 9 in "*Science*", and 73 in "*Physical Review Letters"*. A set of publications from this program was awarded the title "breakthrough of the year 2010" by the *Science* magazine, and one publication was awarded the title "Best research paper published in *Science* 2011" (Newcomb Cleveland award).
The first focus area of the MURI program was bosonic quantum gases in optical lattices. We developed a quantum gas microscope that enables experimenters for the first time to read out individual lattice sites with near perfect fidelity. This gives experimenters unprecedented control, enabling them to directly detect population, correlations and dynamics in quantum simulations on a "single q-bit" level. We studied the quantum phase transition from a superfluid to a Mott insulator on a single site level, and also studied the question of transition dynamics. We realized an algorithmic cooling scheme and demonstrated multi-orbital control. In a different experiment we studied a dual Mott insulator in a magnetic field gradient, realizing a new method of thermometry and adiabatic cooling (spin gradient demagnetization cooling).
The second focus area was strongly interacting fermionic gases. This area is a prime example where quantum simulations are often ahead of theories, and can be used to test and benchmark theoretical approaches. We studied imbalanced Fermi gases with strong interactions, including RF spectroscopy of the fermion pairs, and characterized Fermi gases by density fluctuations. We observed Fermi Polarons in a Tunable Fermi Liquid of Ultracold Atoms. We studied Universal Spin Transport in a Strongly Interacting Fermi Gas, and revealed the Superfluid Lambda Transition in the Universal Thermodynamics of a Unitary Fermi Gas. We developed spin-Injection Spectroscopy of a Spin-Orbit Coupled Fermi Gas as an important new probe. The quantitative measurement of the equation of state in a unitary Fermi gas is an outstanding example for how quantitative quantum simulations can now be used to precisely benchmark theory.
The third focus area of our program is quantum magnetism. We first focused on the search for the ferromagnetic phase transition in the Stoner model for a free Fermi gas with strong interactions. Experiments showed that ferromagnetism does not occur. The experiments triggered new theoretical insights, and lead to a concise theoretical

understanding of the problem, that is of general importance. We then focused on quantum magnetism in optical lattices, and were able to realize a quantum phase transition from a paramagnet to an antiferromagnet in a gas of ultracold atoms. We studied transition dynamics and reached temperatures in the tens of pikokelvin regime, as well as negative temperatures. We developed methods for single spin readout.

Our fourth experimental focus area is molecular gases. We developed new ultra-high flux sources based on buffergas techniques that are now successfully used to load magnetooptical traps for molecules. Together with recent insights that evaporative cooling of molecules is possible this provides a very promising path to stable ultracold gases of non-alkaline polar molecules. We also demonstrated the creation of ultracold Fermionic Feshbach Molecules of 23Na40K to be used as a chemically stable ground state molecular quantum-gas.

The theory tasks in this proposal were focused on guiding experiments and on developing better theoretical understanding of models and systems relevant for ultracold atom quantum simulation. Furthermore theory provided quantitative calculations to which quantum simulations could be compared to, and studied topics motivated by the program but of more general importance.

Theorists in this program proposed a wide range of new models to be realized in ultracold atoms. Areas in which important proposals were made include strongly interacting Fermi systems, Bose-Fermi mixtures, quantum phase transitions in strongly interacting bosonic gases, and molecular gases. A particular focus was quantum magnetism. After the experimental realization of Quantum magnetism in a tilted Mott insulator we undertook various extensions of tilted lattice models in higher dimensions, and found and classified a large number of exotic quantum states. We also studied and proposed J1-J2 XY models, super-exchange based quantum magnetism, and quantum magnetism in gases of polar molecules. Another recent focus were proposals on topologically protected states in ultracold atoms.

Theory also focused on studying heating, dissipation and thermalization – an important subject for quantum simulations. Theorists in our team proposed a wide range of detection schemes that enable measurements in the strongly correlated quantum gases. For example, two complementary approaches for directly measuring entanglement entropy were proposed. Entanglement entropy is an important and powerful concept in theoretical condensed matter physics, but its experimental measurement seemed impossible. The proposals however show that in cold atoms this quantity should be accessible. Other innovative detection schemes are based on measuring fluctuations and their correlations.

A particular important activity of theory groups in our program was to develop interpretations of experimental results, and to carry out calculations to compare with theory. Highlights of this was theory that shed light onto experiments studying the existence of ferromagnetism in strongly correlated Fermi gases, theory connected to the experiments directly measuring the equation of states in Fermi gases, and theoretical calculations connected to experiments in optical lattices.

Last but not least theory worked out new and general concepts. For example were new insights on spin liquids in Kagome antiferromagnets and quantum criticality of metals. An important topic was to identify a holographic dual of quantum critical metal, using entanglement entropy as a probe. A more technical topic was the development of new

numerical techniques, for example tensor network algorithms. These topics were motivated by the program, but are of general importance in condensed matter physics and will have impact far beyond the field of quantum simulation.

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Nature Count: 13
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